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SCENARIO: A Military/Industrial Heat Strain Model Modified to Account for Effects of Aerobic Fitness and Progressive Dehydration

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

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SCENARIO: A MILITARY/INDUSTRIAL HEAT STRAIN MODEL MODIFIED TO ACCOUNT FOR EFFECTS OF AEROBIC FITNESS AND PROGRESSIVE DEHYDRATION

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14. Abstract This report focuses on the development and application of new mathematical algorithms for cutaneous blood flow, sweating rate and cardiac stroke volume for use in SCENARIO, a previously documented computer simulation of physiological responses to work in hot environments. The new algorithms make adjustments for the subject's level of aerobic fitness and the extent of dehydration which can progressively deteriorate performance during sustained exposures. Graphic examples of SCENARIO output are given for sustained work in the normal, euhydrated state and compared with examples of progressive dehvdration and of deteriorated physical fitness due to 20 days of bed rest. An novel example of its use as a tactical decision aide is given.

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Computer models, dehydration, aerobic fitness, skin blood flow, sweating rate, cardiac stroke volume

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FOREWORD

SCENARIO is a six-compartment computer simulation that was specifically designed to mimic body temperature shifts, thermoeffector responses and central circulatory changes of soldiers and emergency personnel in various clothing ensembles while working in hot environments (Kraning, 1991). SCENARIO is one of the heat strain models used at the US Army Research Institute of Environmental Medicine (USARIEM) since 1990 and has also been incorporated into the IUSS dismounted battlefield casualty simulator used by the Soldier Systems Command (SSCOM). SCENARIO exists in both DOS and Windows™ versions.

This note is to document several major changes that make SCENARIO more robust and hopefully more useful to the military user. First, in the original simulation the rate of skin blood flow was controlled with a linear additive model of core and skin temperatures, and further modified only by high levels of physical exertion. Now, reductions in skin blood flow occur as well when progressive losses in plasma volume cause acute dehydration. Second, the sweating rate algorithm originally depended only on deviations in core and skin temperatures. Now, sweating rate control is also related to the degree of aerobic fitness and to the extent of acute dehydration. Third, the model controlling cardiac stroke volume originally depended only on the level of exertion and the extent of cutaneous pooling of blood volume caused by elevated skin temperature. Now, stroke volume depends also on the degree of aerobic fitness and the extent of dehydration.

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EXECUTIVE SUMMARY

This report focuses on the development and application of new mathematical algorithms for cutaneous blood flow, sweating rate and cardiac stroke volume for use in SCENARIO, a previously documented computer simulation of physiological responses to work in hot environments.The new algorithms make adjustments for the subject's level of aerobic fitness and the extent of dehydration which can progressively deteriorate performance during sustained exposures. Graphic examples of SCENARIO output are given for sustained work in the normal, euhydrated state and compared with examples of progressive dehydration and of deteriorated physical fitness due to 20 days of bed rest. An novel example of its use as a tactical decision aide is given.

INTRODUCTION

Computer simulations of human temperature regulation using multi-compartment mechanistic models have been proposed both as general instruments for integrating principles of temperature regulation and as specific tools for studying applied problems such as predicting thermal comfort in buildings and forecasting thermal consequences of cold water immersion, space walks and high intensity RF exposure. (Werner, 1996; Gagge et al, 1971; Stolwijk & Hardy, 1977; Gordon et al, 1976; Kuznetz, 1979; Emery et al, 1976; Wissler, 1985). However, such simulations have not been widely used for predicting physiological responses to work in the heat in industrial or military settings. The original purpose of designing a new computer simulation of thermoregulation (SCENARIO) was to specifically fill this void: to mimic body temperature shifts, thermoeffector responses and central circulatory changes of subjects in various military and industrial clothing ensembles while working in hot environments (Kraning, 1991). In this regard SCENARIO has been used as a planning tool for physiological field studies and in combination with other battlefield casualty models in the Integrated Unit Simulation System (IUSS). Yet neither SCENARIO nor any other extant thermoregulatory simulation incorporates algorithms to account for the degree of a person's physical fitness, which is known to affect cardiac stroke volume and the rate of sweating, or the known deleterious effects of dehydration on sweating rate, stroke volume and skin blood flow. The purpose of this effort was to make SCENARIO more robust by modifying its internal models to account for these militarily relevant factors.

BACKGROUND

Review of SCENARIO Structure

The body is modeled as a single cylinder containing six compartments: (a) a central core representing the heart, the lungs and splanchnic regions, (b) a muscle layer, (c) a subcutaneous fat layer, (d) a vascular skin layer, (e) a superficial avascular

skin layer, and (f) a central blood compartment (Figure 1).

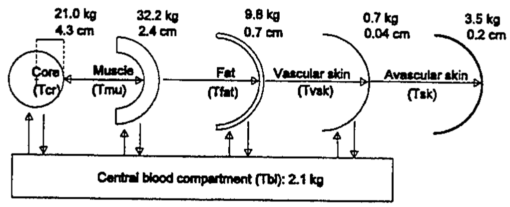

Figure 1.Cross-section of cylindrical model containing 5 concentric annular tissue compartments. Dimensions shown here are for an individual with **W** ≈ 70 kg, $\mathbf{A_D} \approx 1.8$ m^2.

Body Heat Exchange.

In SCENARIO heat is exchanged passively by radial conduction between adjacent compartments, and actively by controlled forced convection of blood through the central blood compartment, core, muscle, fat and skin. From the skin surface heat is lost by air convection, radiation and sweat evaporation to clothing and the surrounding environment. Cylinder and compartment dimensions and thermal conductances are calculated from subject data at program startup.

Intercompartmental Heat Exchange.

Instantaneous thermal mixing is assumed, so there are no temperature gradients within compartments, only temperature differences between compartments. The rate of change of heat content of the six compartments is described by a set of six ordinary differential equations of the form:

$$\frac{d}{dt}Q_n(t) = H_n(t) + \{K_{n-1,n}[T_{n-1}(t)-T_n(t)]\} - \{K_{n,n+1}[T_n(t)-T_{n+1}(t)$$
$$\{BF_n(t)\cdot \rho_{bl}\cdot c_{bl}[T_n(t)-T_{bl}(t)]\} \qquad [W]. \tag{1}$$

where Q_n is the heat content, T_n the temperature, H_n the rate of heat production and BF_n the rate of blood flow through compartment n; T_{bl} is the temperature of the blood compartment, and T_{n-1} and T_{n+1} are the temperatures of compartments adjacent to n. Solution is facilitated by making the assumption:

$$\Delta Q_n(t_m)\Big|_{t_m-\Delta t}^{t_m} \approx \frac{d}{dt}Q_n(t_m)\cdot\Delta t \qquad [W\cdot \text{min}]. \tag{2}$$

Then

$$\Delta T_n(k_m) = \frac{\Delta Q_n(k_m)}{\rho_n c_n V_n} \qquad [C° \text{ or } K] \tag{3}$$

where ρ_n, c_n, V_n, ΔQ_n, and ΔT_n are respectively the density, heat capacity, volume, change in heat content and change in temperature of the *nth* compartment.
The temperature of the *nth* compartment is obtained from the algebraic sum of the collection and the initial temperature condition:

$$T_n(t_i) = T_{n_0} + \sum_{k=1}^{k=i}\Delta T_n(k) \qquad [°C], \quad \textit{where}$$
$$i = \frac{t_i}{\Delta t} + 1 \textit{ and } T_{n_0} \textit{ is the initial temperature.} \tag{4}$$

Δt is set at 0.025 min, but is automatically reduced if thermal drops are severe.

The active system consists of algorithms whose function is to control the rate of blood flow through passive system elements, to modulate the rate of sweat secretion, to adjust the level of conductance between vascular and avascular skin layers, and to set cardiac stroke volume. Inputs to the active system include central blood temperature (T_{bl}), average skin temperature ($\bar{T}_{sk}$), energy expenditure ($\dot{V}o_2$), heat production (H). These algorithms are evaluated anew at each Δt increment.

The addition of fitness level and degree of dehydration to SCENARIO required alteration of algorithms controlling skin blood flow, sweating rate and cardiac stroke volume. Only these will be disc'ssed here. The reader is referred to the original technical report for documentation of the remaining algorithms (Kraning, 91).

DEVELOPMENT OF ALGORITHMS

Skin Blood Flow

The rate of thermoregulatory skin blood flow (BF_{sk}) is known to be a function of central blood temperature (T_{bl}), but is also modulated by mean skin temperature ($\bar{T}_{sk}$), by posture, by work intensity ($\dot{V}o_2$) and, transiently, to the initiation and cessation of exercise (Roberts & Wenger, 1980; Brengelmann, 1983; Johnson & Park, 1982; Johnson, 1986; Johnson et al, 1986). The algorithm used in this simulation for control of BF_{sk} is based primarily on an empirical regression model of Roberts and Wenger's data during upright exercise and heat stress, but it also incorporates effects of activity level as inferred from work of Johnson (Roberts & Wenger, 1980; Johnson, 1986).

Control of BF_{sk} is modeled as a linear function of T_{bl}. Both $\bar{T}_{sk}$ and $\dot{V}o_2$ shift this function's threshold temperature (Th_{BFsk}): increasing $\bar{T}_{sk}$ lowers Th_{BFsk} while increasing $\dot{V}o_2$ increases Th_{BFsk}. Exercise also produces graded reductions in the upper limit for skin blood flow ($MaxBF_{sk}$): from 7.0 $l \bullet min^{-1}$ at rest to 5.0 $l \bullet min^{-1}$ at a $\dot{V}o_2$ of >2.0 $l \bullet min^{-1}$ (Johnson, 1986). Based on data of Fortney et al., increasing plasma osmolarity accompanying weight loss ($\downarrow$**W**)during dehydration increases Th_{BFsk} by 0.06°C for each percent decrease in **W** (%$\downarrow$**W**), while the slope or gain (α_{BFsk}) decreases by -0.13 $l \bullet min^{-1} \bullet C^{-1}$ for each %$\downarrow$**W** and $MaxBF_{sk}$ during exercise decreases by 0.10 $l \bullet min^{-1}$ for each%$\downarrow$**W** (Fortney et al, 1984).

Minimum BF_{sk} is set at 0.03 l•min^{-1}. The presumption is made that all "rest" will be in the upright seated position and that all "work" will be in the upright standing position. Maximal skin blood flow ($MaxBF_{sk}$) is defined by the piecewise continuous function:

$MaxBF_{sk} = 7.00$ l•min^{-1} for $\dot{V}O_2 \leq 0.5$ l•min^{-1}; [5a]

$MaxBF_{sk} = 7.00 - 1.33(\dot{V}O_2 - 0.50)$ l•min^{-1} for 0.50 l•min^{-1} < $\dot{V}O_2$ < 2.00 l•min^{-1}; [5b]

$MaxBF_{sk} = 5.00$ l•min^{-1} for $\dot{V}O_2 \geq 2.00$ l•min^{-1}. [5c]

During gradual dehydration $MaxBF_{sk}$ is modified by ΔMax BF_{sk}:

$\Delta Max\ BF_{sk} = (0.1) \bullet \%\downarrow\mathbf{W}$ (l•min^{-1}) [5d]

$MaxBF_{sk} = (7a, 7b \text{ or } 7c) - (\Delta Max\ BF_{sk})$ [l•min^{-1}] [5e]

BF_{sk} is defined in terms of a percentage of $MaxBF_{sk}$:

$Pct\ MaxBF_{sk} = \alpha_{BFsk} \bullet (T_{bl} - Th_{bl\text{-}BFsk})$ [%]. [6]

where $\alpha_{BFsk} = 70.3\% \bullet °C^{-1}$ or [7a]

$\alpha_{BFsk} = 70.3\ (1 - 0.13 \bullet \%\downarrow\mathbf{W}) \bullet °C^{-1}$ for $\%\downarrow\mathbf{W} > 0$; [7b]

and$Th_{bl\text{-}BFsk}$, the threshold blood temperature is defined by:

$Th_{bl\text{-}BFsk} = 37.07 - 0.108(\bar{T}_{sk} - 30.0)$ for $\dot{V}O_2 \leq 0.75$ l•min^{-1}; or [8a]

$Th_{bl\text{-}BFsk} = 37.32 - 0.093(\bar{T}_{sk} - 30.0)$ for $\dot{V}O_2 > 0.75$ l•min^{-1}, $\bar{T}_{sk} \leq 33.0°C$; or [8b]

$Th_{bl\text{-}BFsk} = 37.04 - 0.030(\bar{T}_{sk} - 33.0)$ for $\dot{V}O_2 > 0.75$ l•min^{-1}, $\bar{T}_{sk} > 33.0°C$. [8c]

During gradual dehydration $Th_{bl\text{-}BFsk}$ progressively increases by $\Delta\ Th_{bl\text{-}BFsk}$:

$\Delta\ Th_{bl\text{-}BFsk} = (0.06°C) \bullet \%\downarrow\mathbf{W}$ for $\%\downarrow\mathbf{W} > 0$ [8d]

$Th_{bl\text{-}BFsk} = (10a, 10b \text{ or } 10c) + \Delta\ Th_{bl\text{-}BFsk}$ [8e]

Finally, BF_{sk} is:

$BF_{sk} = (MaxBF_{sk})(Pct\ MaxBF_{sk})/100$ (l•min^{-1}). [9]

<u>Sweating Rate</u>

Sweating rate is basically modeled as a function of central temperature (T_{bl}), mean skin temperature ($\bar{T}_{sk}$) and their corresponding threshold temperatures ($Th_{bl\text{-}SR}$ and $Th_{sk\text{-}SR}$). This equation, originally proposed by Nadel et al, has herein been modified to include the effect of physical training and the effects of dehydration (Nadel <u>et al</u>, 1971).

Buono and Sjoholm showed a direct relationship between the local sweating response to a fixed cutaneous dose of pilocarpine and the subject's $\dot{V}O_2max$ (Buono & Sjoholm, 1988). Their relationship is used to calculate a new multiplicative term, λ_{SR}. The assumption is made that the value of λ_{SR} for their normal young sedentary male subjects ($\dot{V}O_2max$ = 3.65 l•min^{-1}) is unity. Then,

$$\lambda_{SR} = \frac{(160 \cdot VO_2\text{max}/\boldsymbol{W}) - 3.2}{3.84}. \qquad [10]$$

The equation for sweating rate then becomes:

$$\dot{m}_{sw} = A_D \lambda_{SR} \left(\alpha_{SR}[T_{bl} - Th_{bl\text{-}SR}] + \beta_{SR}[\bar{T}_{sk} - Th_{sk\text{-}SR}] \right) \exp\left(\frac{\bar{T}_{sk} - Th_{sk\text{-}SR}}{\delta_{SR}} \right) \qquad (11)$$

Nominal values for the coefficients are α_{SR} = 4.83, β_{SR} = 0.56, and δ_{SR} = 10, and for the threshold temperatures are $Th_{bl\text{-}SR}$ = 36.96 and $Th_{sk\text{-}SR}$ = 33.0 (Nadel et al, 1971).

Montain et al. (1995) studied the change in α_{SR} and $Th_{bl\text{-}SR}$ during progressive dehydration and found that α_{SR} decreased and $Th_{bl\text{-}SR}$ increased:

$$\Delta\, \alpha_{SR} = (-0.6 \text{ g} \cdot \text{min}^{-1} \cdot {}^{\circ}\text{C}^{-1}) \cdot \%{\downarrow}\mathbf{W}, \text{ and} \qquad (13)$$

$$\Delta\, Th_{bl\text{-}SR} = (0.06\ {}^{\circ}\text{C}) \cdot \%{\downarrow}\mathbf{W}. \qquad (14).$$

These changes are incorporated into the calculation as progressive changes in body water content occurs.

Cardiac Stroke Volume.

The value of stroke volume (SV) is influenced by many factors. Factors considered here are: the level of work ($\dot{V}O_2$), the level of $\bar{T}_{sk}$, the degree of physical fitness ($\dot{V}O_2$max), and the severity of dehydration (%↓**W**).

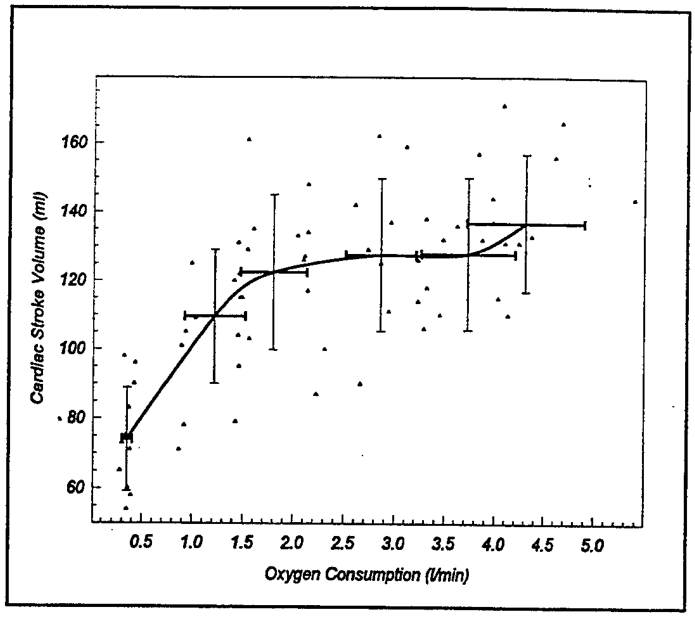

Figure 2. SV as a function of VO_2 in 12 male subjects. Data of Åstrand et al, 1964.

A study of Åstrand et al. on changes in SV during graded upright ergometer exercise of twelve male subjects (Figure 2) is the basis for SCENARIO's normal stroke volume calculations. They showed that "normal" stroke volume (SVn) increases fairly linearly from a minimum value (SVn_{min}) at very low levels of work to a maximum value (SVn_{max}) at a work rate roughly equal to 2 l O_2•min^{-1} (Åstrand et al, 1964).This range is important since it encompasses most day-to-day work in the military and in heavy industry. Replotting the values for SVn_{min} and SVn_{max} by subject (Figure 3) demonstrates a correlation with the magnitude of the subject's $\dot{V}O_2$max. Linear least-squares equations are used to establish values for SVn_{min} and SVn_{max} in the model:

$$SVn_{min} = 67 + 20.61 \bullet (\dot{V}O_2max - 2.0) \text{ [ml]} \quad [15a]$$

$$SVn_{max} = 80 + 25.67 \bullet (\dot{V}O_2max - 2.0) \text{ [ml]} \quad [15b]$$

The assumed lower limit on $\dot{V}O_2$max is 2.0 l •min^{-1}.

Normal stroke volume (SVn) is now defined in terms of SVn_{min} ,SVn_{max} and $\dot{V}O_2$:

$$SVn = SVn_{min} \quad \text{for } \dot{V}O_2 \leq 0.5 \text{ l} \bullet min^{-1} \quad [16a]$$

$$SVn = ((SVn_{max} - SVn_{min}) / 1.5)(\dot{V}O_2 - 0.5) + SVn_{min}, \text{ for } 0.5 \text{ l} \bullet min^{-1} < \dot{V}O_2 < 2.0 \text{ l} \bullet min^{-1} \quad [16b]$$

$$SVn = SVn_{max} \quad \text{for } \dot{V}O_2 \geq 2.0 \text{ l} \bullet min^{-1} \quad [16c]$$

Once SVn is obtained, the detrimental effects of elevated $\bar{T}_{sk}$ and of dehydration

are considered. As $\bar{T}_{sk}$ rises, SVn is diminished because of displacement of central intravascular volume into cutaneous veins (Rowell, 1983). This aspect of SV control is modeled in the following way. As energy expenditure and SVn increase, the impact of increasing $\bar{T}_{sk}$ becomes more pronounced and SV can be as much as 25 ml lower than when $\bar{T}_{sk}$ is cool. The equations describing $\bar{T}_{sk}$ decrement in stroke volume (ml_{Tsk}) are:

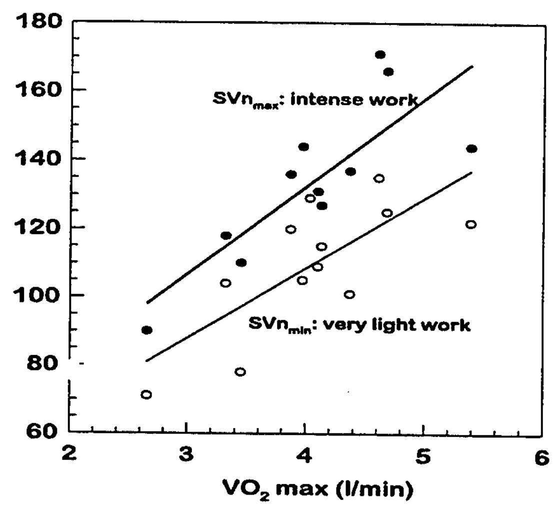

Figure 3. Lower and upper limits on Svn during light and maximal work as a functin of maximal oxygen consumption. Plotted from data of Åstrand et al.`1964.

$ml_{Tsk} = 0$ for $\bar{T}_{sk} \leq 33.0°$ C; [17a]

$ml_{Tsk} = 5[\bar{T}_{sk} - 33.0][(SVn - SVn_{min})/(SVn_{max} - SVn_{min})]$, for $33.0°$ C $< \bar{T}_{sk} \leq 38.0°$ C; [17b]

$ml_{Tsk} = 25\ [(SVn - SVn_{min})/(SVn_{max} - SVn_{min}\ ]$, for $\bar{T}_{sk} > 38.0°$ C. [17c]

Progressive dehydration decreases SVn as well. Nadel et al showed an almost one for one relationship between the decrement in SVn and the percentage fall in plasma volume (Nadel et al, 1980):

$ml_{dehyd} = 1.03 \bullet \%\downarrow Pl\ Vol$, [18a]

where %↓Pl Vol during dehydration is estimated from %↓**W** using (Saltin, 1964)

$\%\downarrow Pl\ Vol = 4.37 \bullet \%\downarrow \mathbf{W}$. [18b].

Then, SV is simply:

$SV = (SVn) - (ml_{Tsk}) - (ml_{dehyd})$ [19].

Change-of- state lags.

Discontinuities in physiological responses occurring during the transition between exercise levels can be particularly troublesome when transitioning to rest. First-order lags are introduced in order to restrain large, sudden changes in calculated blood flows and cardiac stroke volume that would otherwise accompany change-of-state discontinuities. These lags are described by:

$$X_{m+1} = X_m + (X_{ncv} - X_m)\left[1 - \exp\left(\frac{-0.693\,t_m}{t_{0.5}}\right)\right], \qquad \text{where} \qquad [20]$$

X_{m+1} is the new time-lagged value for variable X, X_m is the time-lagged value for X during the last recalculation interval, X_{ncv} is the new non-lagged value for X as calculated by the algorithm, t_m is the elapsed time into the current time of interest period and $t_{0.5}$ is the response half-time (from 30 sec to 2 min, depending upon the variable).

MODEL IMPLEMENTATION.

The simulation was developed as an interactive DOS program but recently has been restructured to run as a Windows™ application. Program inputs include subject

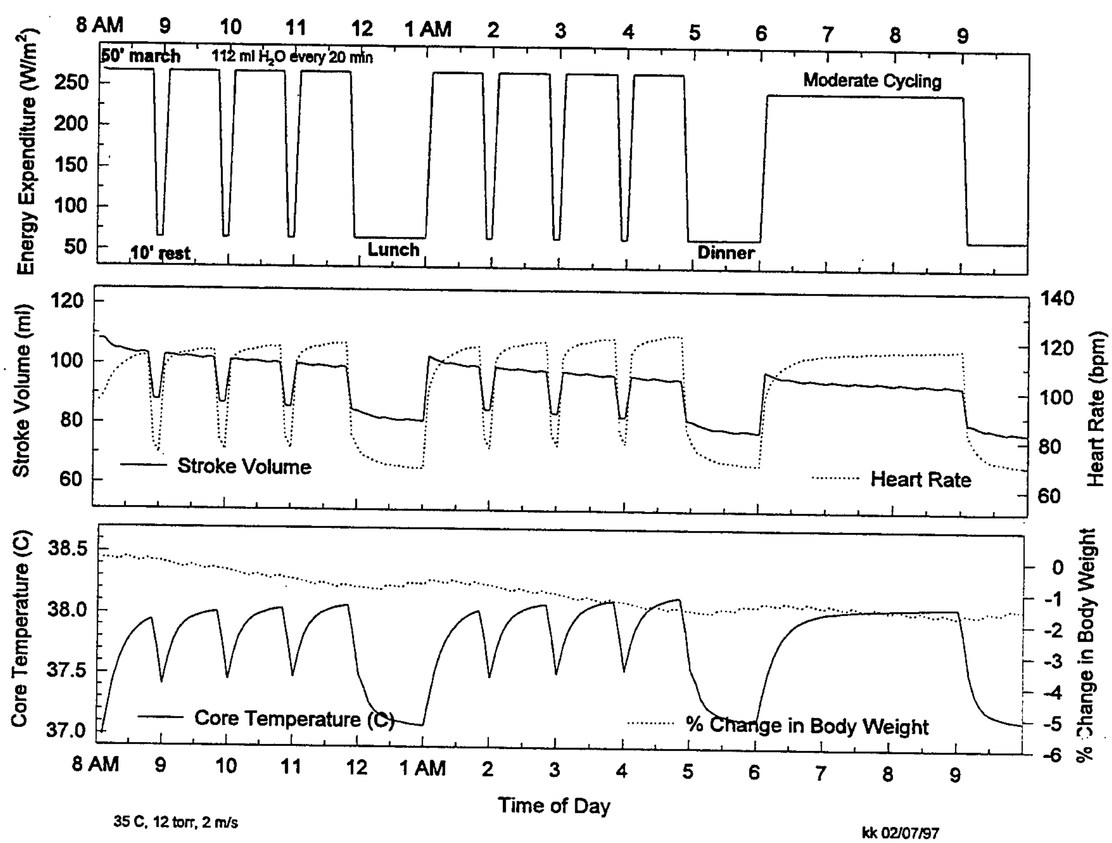

Figure 4. Simulated effect of sustained training and recreational activities on an average soldier's body core temperature, heart rate and stroke volume over the course of a day. Environment held constant at 30°C, 29% RH and air movement at 2m/sec. This was moderate activity on a mild summer day and well within the capacity of the average young soldier. The "subject" replaced sweating losses by drinking 112 ml of H_2O every 20 min. Dehydration was limited to less than 2% of body weight, SV was maintained and core temperature achieves stable levels.

anthropometric data (stature, weight, age, percent body fat, $\dot{V}o_2max$), clothing insulation and water vapor permeability, environmental variables (air temperature, humidity and air movement), type and intensity of exercise (leg work, arm work or rest; walking speed

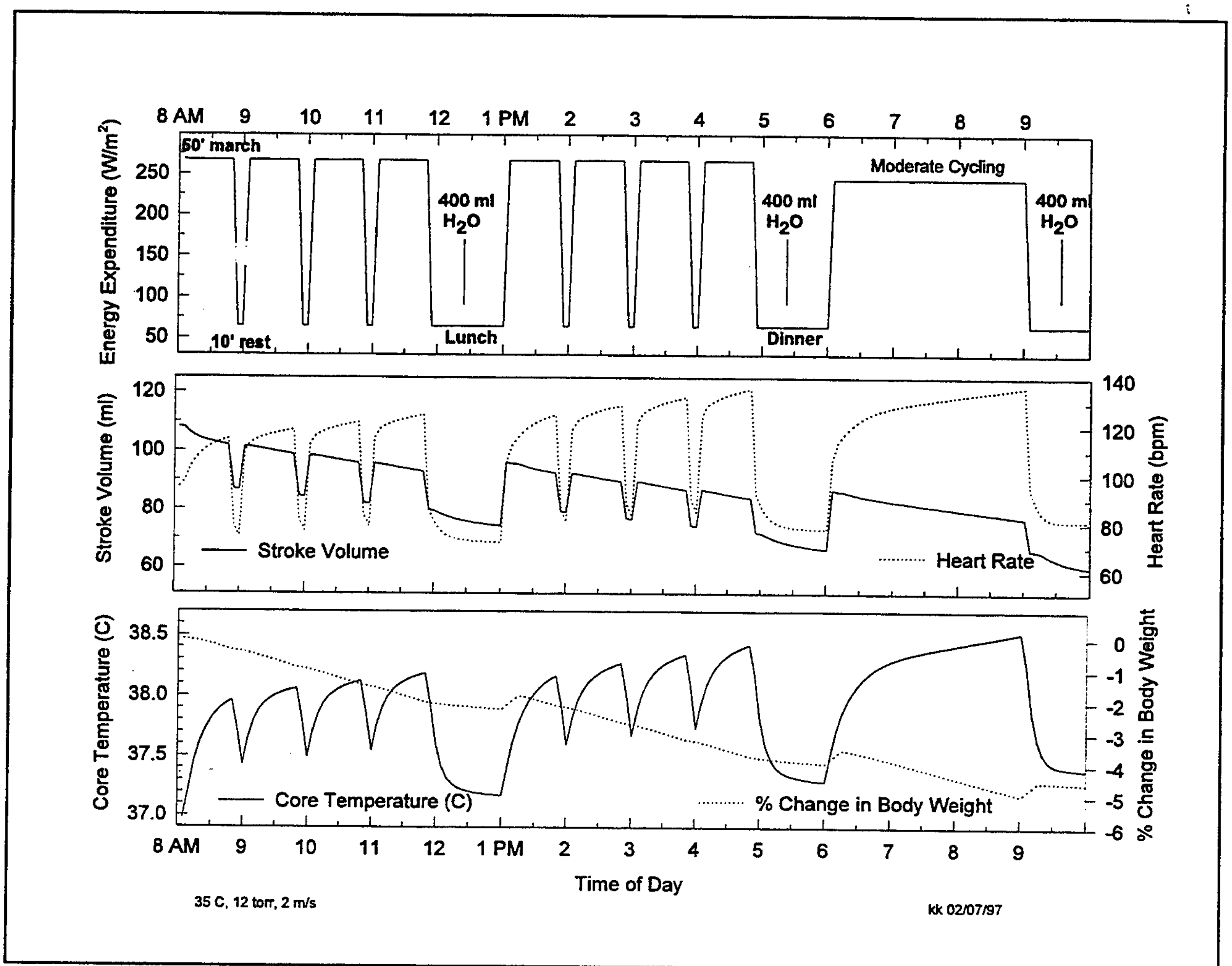

Figure 5. The same circumstances as Fig 4 except that water replacement was inadequate and the "subject" lost a total of 5% of his body weight during the day. Althoug^h cardiac output and sweating rate (not shown) were maintained, it was at greater physiological cost in terms of heart rate and core temperature elevation.

and grade or energy expenditure), water replacement and length of time cycles. The time course of all compartment heat flows, temperatures and blood flows, heat storage, sweating rate and total fluid loss, cummulative energy expenditure, cardiac output, heart rate and stroke volume are available as outputs. Values necessary for analysis by traditional heat stress indices based on partitional calorimetry are computed as well.

Threshold temperatures for T_{bl} and for $\bar{T}_{sk}$ are set at 36.96°C and 33.0°C, respectively. These were determined empirically by programing the simulation as a subject at rest in a comfortable environment for 4 to 6 hrs and permitting it to seek equilibrium.

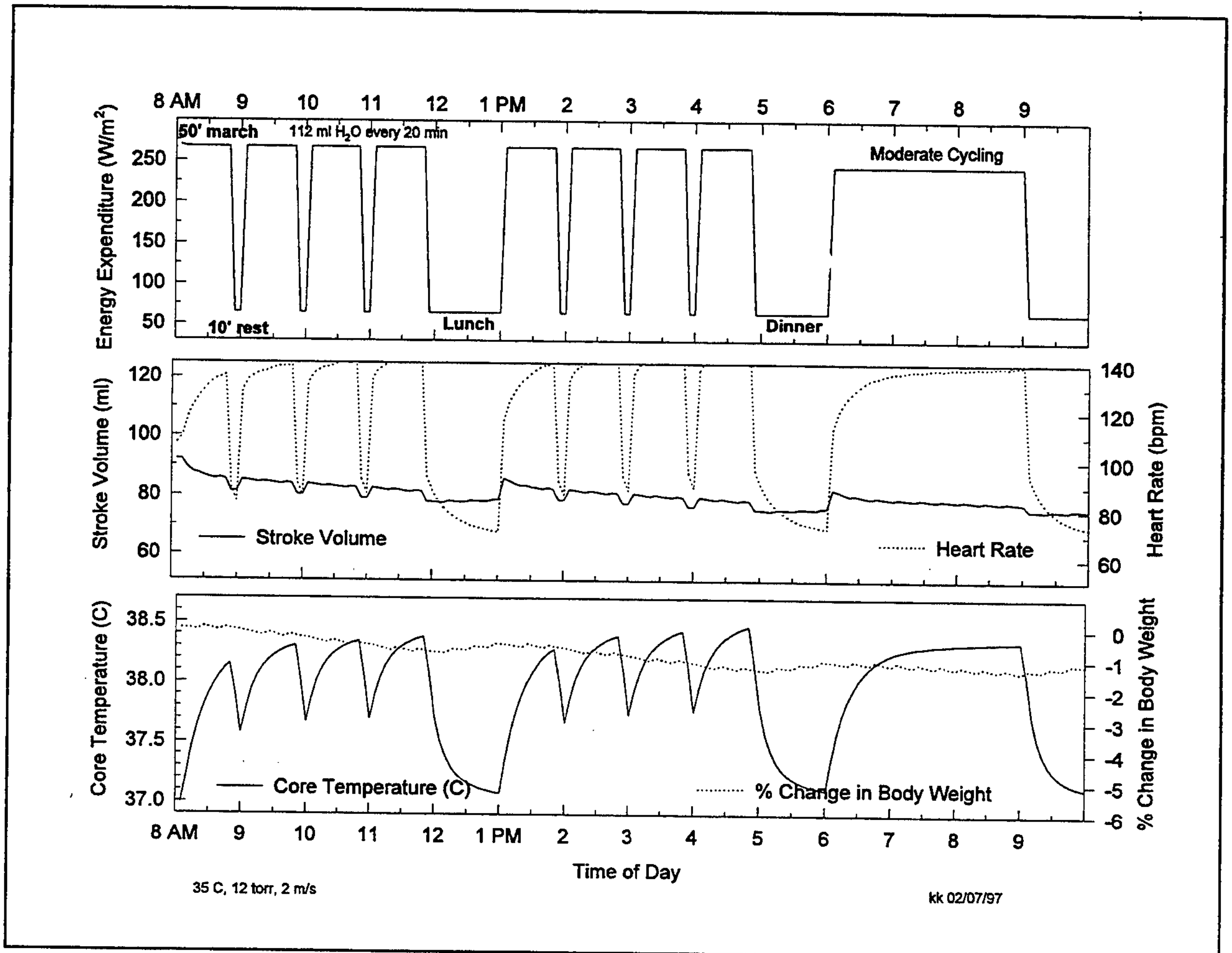

Figure 6. Same subject and simulation protocol as in Figure 4. Subject was deconditioned by 20 days of bedrest reducing VO_2max 20%: from 3.40 $\ell \cdot min^{-1}$ to 2.72 $\ell \cdot min^{-1}$. Note the increased physiological cost in terms of core temperature and heart rate elevation for the same task performance.

SCENARIO can be programed for a period as short as 10 minutes or for several days with any combination of activity levels and rest periods desired. Moment to moment changes in outputs can be automatically saved to a spreadsheet file.

Figure 4 demonstrates the simulated sustained responses of heart rate, stroke volume and core temperature to a recruit's training and recreation program over the course of a mild summer day. Water was replaced regularly (112 every 20 min) and dehydration was not a significant problem. Note that stroke volume and core temperature responses were stable and reached steady state.

Contrast this with the case of inadequate water replacement and progressive dehydration over the same day period (Figure 5). Because water replacement was inadequate, this "subject" lost about 5% of his body weight (3.5 kg or liters). Even though SV fell throughout the day because of increasing dehydration, cardiac output was maintained: the falling SV was compensated but at the expense of an increasing HR. The same is true for sweating rate. Dehydration both raises the threshold core temperature for sweating and diminishes the sensitivity of sweat production to changes in core temperature. Thermoregulatory integrity is maintained during the day at the expense of elevated core temperature which is forced to increase in order to restore an adequate drive to the sweat glands. Thus, even under conditions of moderate exposure, dehydration increases the physiological cost of thermoregulation and undoubtedly limits endurance and performance.

Saltin et al. have shown that VO_2max in healthy young males is decreased by 20% after 21 days of strict bedrest (Saltin et al, 1968). Our soldier in Fig 4 had a VO_2max of 3.40 l •min^{-1}. Assuming he had to be hospitalized for 21 days, his VO_2max might drop 20 %, to 2.72 l •min^{-1}. Figure 6 demonstrates the consequences of this large drop in terms of the increased physiological cost of sustained work.

SUMMARY AND CONCLUSIONS

We have taken a computer simulation of physiological reactions to the stresses of heat and work (SCENARIO) and attempted to make it more robust by modifying the algorithms for cutaneous blood flow, sweating rate and cardiac stroke volume to account for the state of physical fitness and the extent of dehydration. We have shown that even moderate changes in either water balance or maximal oxygen consumption

can seriously alter the physiological cost of thermoregulation. Through these changes SCENARIO should be better able to answer tactical "What if?" questions. For example, the simulation could be set to more accurately reflect the physical condition of the particular group of troops under consideration. Starting with an acceptable casualty level, the simulation could be used to forecast water and caloric requirements and to plan rest and recovery periods during sustained operations.

SCENARIO can be used as a decision aid in other ways. An example is with the

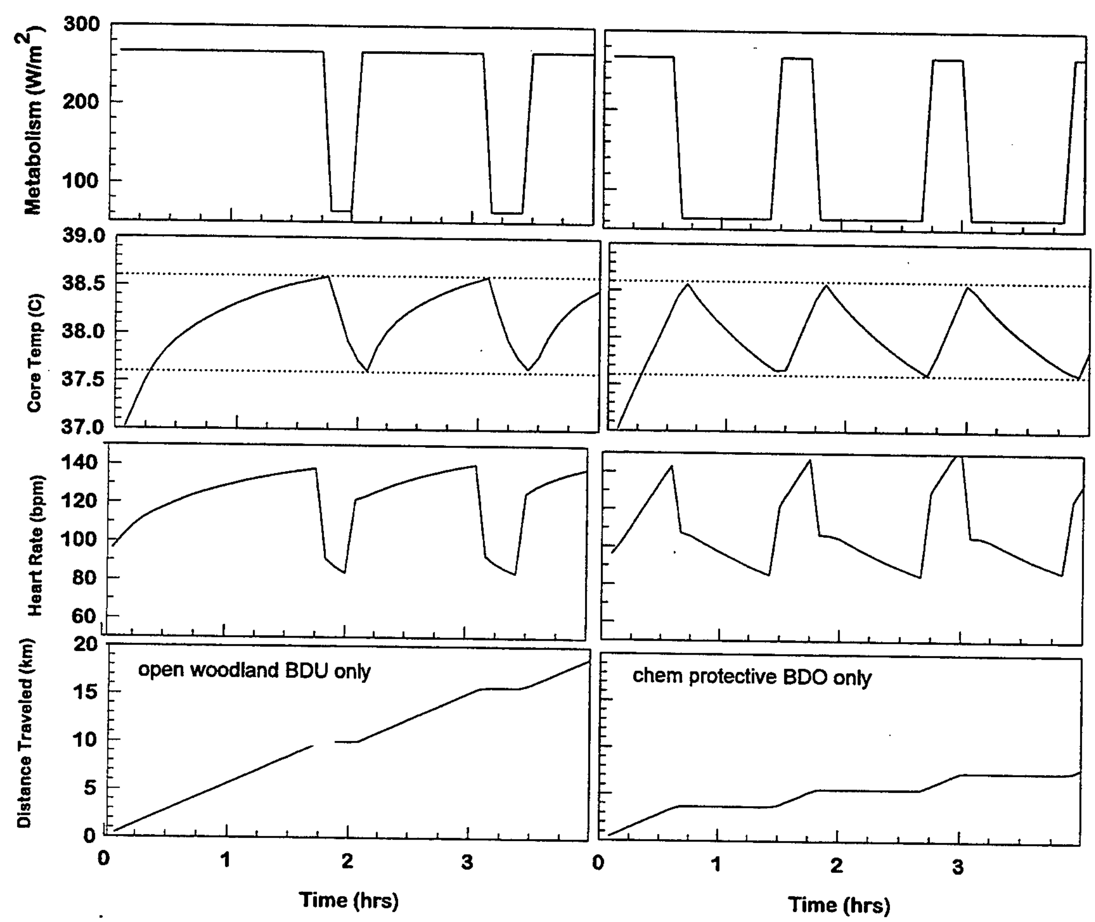

Figure 7. Using SCENARIO as a tactical tool during sustained operations. Soldier is wearing a personal protective device that measures his core temperature. Instructions are to rest when T_{cr} reaches 38.6 °C and return to marching when T_{cr} falls to 37.6 °C. Wearing chemical protective clothing reduces the distance covered in four hours from 18.8 km to 7.9 km.

use of personal monitoring devices that alarm the soldier when his body temperature and/or heart rate have reached a critical level. There is an executive need to predict the impact of using these personal safety monitors on the mission plan. For instance the soldier may be instructed to stop work when T_{cr} exceeds 38.6°C and to return to work when T_{cr} has receeded to 37.6°C. The question arises, "How long will it take to perform the mission?" SCENARIO can be programed to automatically change metabolic rate from marching to rest and back again when these upper and lower limits are exceeded and keep track of the distance traversed. Figure 7 is an example of this application demonstrating the trade-off in performance that must be accepted when wearing chemical protective clothing.

Computer simulations of physiological function are always built upon a knowledge base. If the knowledge base is flawed or incomplete, the simulation will also be flawed or incomplete. While the proposed changes to SCENARIO are qualitatively correct, data for definitive validation are almost non-existant. This is especially true with respect to gender. Even well-trained females are known to have lower values for $\dot{V}O_2max$ and SV than their male counterparts. It may be that in cases of work in heat exposure where the endurance of a male soldier is limited by body temperature rise, the female soldier, having less central circulatory reserve, may sucumb sooner than the male and for different reasons. More basic research on gender differences in these areas is needed.

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